NAVAL MEDICAL RESEARCH UNIT DAYTON

FIELD OF VIEW EVALUATION FOR FLIGHT SIMULATORS USED IN SPATIAL DISORIENTATION TRAINING

WILLIAMS, H.P., LITTMAN, E.M., FOLGA, R.V., PATTERSON, F.R.

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J. M. Andrews

Jeffrey M. Andrews, CAPT, MSC, USN
Commanding Officer

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Henry P. Williams, Ph.D., Eric M. Littman, Ph.D., Richard V. Folga, M.A., and Frederick R. Patterson, Ph.D.

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14. ABSTRACT
Spatial disorientation (SD) is a deadly threat to aviation safety, so it is important to train pilots to recognize, avoid, and/or recover from it. Flight simulation is a safe and relatively inexpensive vehicle for SD training, but certain simulator characteristics, such as the field of view (FOV) required for effective training, need to be better specified. These specifications then need to be applied in upgrades to simulators used in SD training. This project examined three different FOVs and their ability to induce specific responses associated with SD, namely the Opto Kinetic Cervical Reflex (OKCR) and Control Reversal Error (CRE). Twelve pilots flew a simulator in two different scenarios using a Small, Medium, and Large FOV. The results indicated that under these conditions the Medium FOV was an optimum choice for eliciting the OKCR and CREs, since it generally outperformed the Small FOV and equaled the Large FOV, all at a lower price point and with a smaller footprint. This information is being directly applied to the Advanced SD Training simulator acquisition process that is currently underway at NAVAIR PMA-205, Aviation Training Systems. The results are applicable to other simulator systems as well, and implications and recommendations for SD training are discussed.

15. SUBJECT TERMS
Spatial Disorientation (SD), Opto Kinetic Cervical Reflex (OKCR), Field of View (FOV), Control Reversal Error (CRE), Flight Simulator, Spatial Disorientation Trainer, Spatial Disorientation Simulator

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CAPT Jeffrey M. Andrews
Commanding Officer
Naval Medical Research Unit Dayton

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Abstract

Spatial disorientation (SD) is a deadly threat to aviation safety, so it is important to train pilots to recognize, avoid, and/or recover from it. Flight simulation is a safe and relatively inexpensive vehicle for SD training, but certain simulator characteristics, such as the field of view (FOV) required for effective training, need to be better specified. These specifications then need to be applied in upgrades to simulators used in SD training. This project examined three different FOVs and their ability to induce specific responses associated with SD, namely the Opto Kinetic Cervical Reflex (OKCR) and Control Reversal Error (CRE). Twelve pilots flew a simulator in two different scenarios using a Small, Medium, and Large FOV. The results indicated that under these conditions the Medium FOV was an optimum choice for eliciting the OKCR and CREs, since it generally outperformed the Small FOV and equaled the Large FOV, all at a lower price point and with a smaller footprint. This information is being directly applied to the Advanced SD Training simulator acquisition process is currently underway at NAVAIR PMA-205, Aviation Training Systems. The results are applicable to other simulator systems as well, and implications and recommendations for SD training are discussed.

Field of View Evaluation for Flight Simulators Used in Spatial Disorientation Training

Henry P. Williams, Ph.D., Eric M. Littman, Ph.D., Richard V. Folga, M.A., and Frederick R. Patterson, Ph.D.
Naval Medical Research Unit Dayton

Aviation spatial disorientation (SD) can be described as a pilot's inability to correctly interpret aircraft attitude and motion in relation to the earth or other points of reference (11). If not recognized immediately, these misperceptions can lead to controlled flight into the ground, midair collision, or inappropriate control inputs resulting in aircraft stall and departure from controlled flight. The magnitude of this problem has been well documented by mishap reports and surveys that indicate virtually all pilots experience some form of SD during their careers (3, 8). Naval Safety Center accident statistics indicate that SD is the number one aeromedical causal factor in Class A mishaps (loss of life or greater than $2 million in property damage), and that it is a causal factor in 28.6% of these serious accidents (2). On average, each year SD results in the deaths of 25 flightcrew, the destruction of at least 20 Department of Defense (DoD) aircraft, and asset losses of over 400 million dollars (10).

In 2011, NAMRU-D began collaborating with the Naval Air Systems Command (NAVAIR) and the Naval Survival Training Institute (NSTI) to develop SD training scenarios for integration into the Naval Aviation Survival Training Program. Since 2005, NSTI has provided hypoxia familiarization training using the reduced-oxygen breathing device (ROBD), often times delivered during authentic aviator flight simulation events. In February 2012, NSTI accepted delivery of a prototype part-task training simulator system intended to provide both a hypoxia familiarization training platform and SD training content. However, the candidate system was not delivered with any SD training capability, and the visual display suite selected were inadequate for that purpose. The delivered configuration included three flat panel TV liquid crystal displays which were arranged vertically side-by-side in front of the pilot. The frame of each display created an artificial border that interrupted the out-the-window (OTW) scene in a distracting and unrealistic manner. Furthermore, these vertical borders provided spatial cues that are not present in fleet aircraft, and these cues would have interfered with SD training in unwanted and unpredictable ways. NAVAIR needed assistance in developing specifications for a cost effective visual system upgrade to support proper SD training, and that need was the impetus for this project.

One simulator design variable that can greatly affect cost is field-of-view (FOV) size. As FOV increases more pixels are needed to maintain a given resolution. More pixels can be provided by adding projectors or displays, or by using higher resolution projectors/displays, but either solution increases system cost.

The choice of FOV size should be driven by a determination of how much FOV is needed to support a given training task. Different tasks can require different FOVs. For example, for training straight-in landing approaches in instrument meteorological conditions (IMC), relatively small FOVs may suffice because most of the important OTW visual information is directly in front of the pilot, and in IMC, much of this is obscured by clouds. There is very little to see until the flight gets closer to the ground and enters the runway environment. However, for SD training a larger FOV may be needed to recreate certain spatial cues and responses to those cues. One vestibular spatial response that is thought to play

a role in SD is the Opto Kinetic Cervical Reflex (OKCR), also known as the head tilt reflex. In this reflex the pilot tries to keep the horizontal (transverse) plane of his/her head aligned with the horizon. For example, when a pilot banks an aircraft to the left, he/she will reflexively tilt his/her head to the right in an effort to maintain alignment with the visible natural horizon. If the horizon becomes obscured by clouds and the pilot has to transition to instruments, this head tilt ceases and the pilot will realign his/her head with the Z axis (i.e., the vertical cockpit axis). In general, larger FOVs tend to increase the strength of the OKCR (5, 12).

Identification of OKCR has led to the realization that during sustained turns with intermittent IMC, inaccurate perceptions of aircraft bank may also be triggered by the reflexive head tilt behavior. Because head position in the cockpit will determine how the vestibular system reacts to sustained accelerations encountered during a coordinated turn, reflexive head movements caused by rapid environmental changes may create intravestibular conflict capable of generating unreliable sensations of tilt. For example, if a pilot enters the banked portion of a holding pattern while flying in and out of clouds, his/her OKCR response will cycle on and off as the intermittent cloud cover causes the outside horizon to repeatedly appear and disappear. Consequently, as his/her head tilts on and off the cockpit vertical axis (Z axis), the vestibular system will continue to receive conflicting acceleration information from the otoliths and semicircular canals, thereby increasing susceptibility to this false sensation of tilt, also known as the "leans." In turn, a potentially dangerous consequence of the leans is control reversal error (CRE), where the pilot makes a stick input in the wrong direction because of confusion between the vestibular and visual senses. A spatially disoriented pilot flying in the clouds may have the leans as a result of the OKCR and feels that the aircraft is in a left bank when in fact it is in a right bank. The pilot looks at the attitude indicator, confirms that the aircraft is banked, but misinterprets the direction of bank. Believing he/she is banked left, the pilot moves the stick to the right, committing a CRE. The pilot banks further to the right, becomes more disoriented, and is at serious risk of departing controlled flight and crashing if there is not enough altitude for recovery. The SD in this hypothetical but very plausible scenario was triggered by the OKCR.

If the CRE scenario above could be recreated in the safe confines of a flight simulator, it would provide a very effective means for teaching pilots how to avoid, recognize, and/or recover from this common form of SD. In order to design such a simulation properly, one question that must be answered is: "What is the optimum size FOV for eliciting head tilt and a realistic CRE response?" Previous work has shown that larger FOVs tend to increase the amount of OKCR head tilt, and thereby help preserve what are thought to be crucial visual spatial cues related to CRE (5, 12); however, the FOVs in these experiments were manipulated with either head-mounted displays (HMDs) or head worn occlusion masks that prevented normal OTW cockpit views with the use of peripheral, or secondary spatial cues (i.e., glareshield or cockpit parts; 5, 12). Since neither of these methods was able to replicate typical pilot sight pictures, a preferred method would be to evaluate the effect of FOV on OKCR using flight simulators that are more representative of normal cockpit views and which are currently in wide use in the aviation training community.

The principal goal of this effort was to determine the extent to which variations in simulator FOV affect the ability to induce OKCR and CRE, using three different FOV sizes and a flight simulator system that is

similar to those found in the military aviation training environment. Advantages to simulators with smaller FOVs are that they are generally less expensive and occupy less space, other factors being equal. NAVAIR is actively seeking input on specifications for planned acquisition of SD training systems, and this project is specifically aimed at providing guidance on the best FOV for those simulators. Specifying the optimum FOV for SD simulator procurement will help ensure that aircrew are provided with effective SD training in a fiscally responsible manner.

METHOD

Participants

Twelve pilots (eleven male, one female) participated in this study, and their total flight time ranged from 100 to 5000 hours, with a mean of 2089 hours. Seven of the twelve had experience as military pilots and the remaining five had at least a civilian Private Pilot License. Ages ranged from 18 to 65 years, with a mean of 44.6 years.

Experimental Design

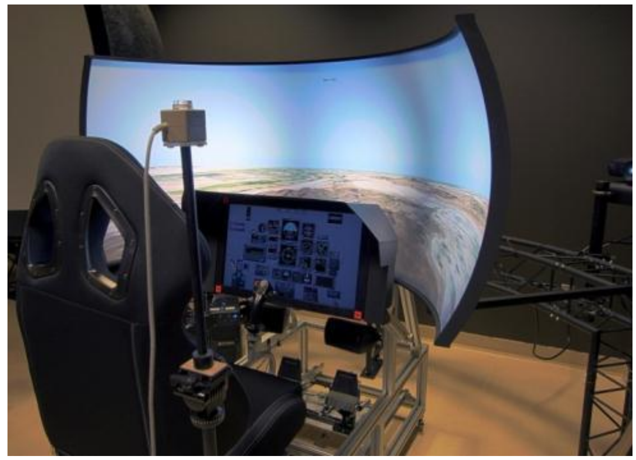
This study used a single factor repeated-measures (within-subjects) design. The independent variable, simulator FOV, had three levels: Small, Medium, and Large, as detailed below.

Equipment and Procedures

The OTW scene for the simulated flights was presented using three different FOVs (see Figure 1). The Small FOV measured 87° horizontally x 49° vertically and was created using a 60 inch diagonal Samsung UN60ES7500FXZA Slim LED High Definition 1080p flat panel display (Figure 1A). The Medium FOV measured 130° horizontally x 60° vertically. This system used an Immersive Display Solutions™ three-channel back-projected 1.5 meter diameter acrylic spherical display, with three Digital Projection iVision SXGA+™ projectors (Figure 1B). The Large FOV measured 180° horizontally x 90° vertically. This three-channel system was also produced by Immersive Display Solutions, but was front-projected using a 3.0 meter diameter dome with three Digital Projection iVision WUXGA™ projectors (Figure 1C).

Switching between FOVs was accomplished by moving the cockpit, which was equipped with wheels, into position in front of each visual system. The cockpit (see Figure 2) was modeled after a T-6A Texan II aircraft, which is the primary flight trainer for the U.S. Navy, Marine Corps, Coast Guard and Air Force. The fixed-base simulator used Laminar X-Plane™ version 10.0 of the T-6A flight model. Engine power was controlled via a Thrustmaster Warthog™ throttle module, and pitch and roll were controlled via a Thrustmaster Cougar™ joystick. The cockpit was equipped with a SPARCO™ seat that was adjustable in height. Cockpit instruments were displayed on a 26 inch diagonal ELO™ monitor.

A



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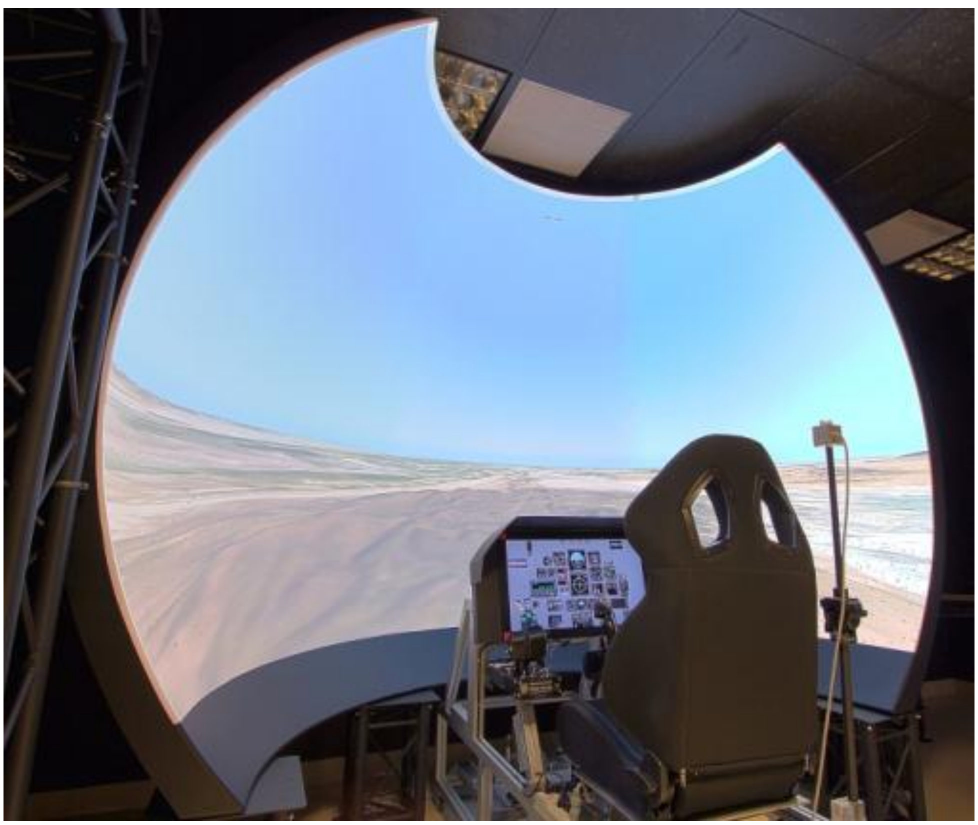

C

Figure 1. Photographs of the three out-the-window display systems used in this experiment: (A) Small FOV, (B) Medium FOV and (C) Large FOV.

Figure 2. The T-6A flight simulator cockpit.

An ISCAN AA-ETL-600 Head and Eye Tracking System™ was used to track and record the head and eye movements of the participants (see Figure 3). This tracking system was able to measure head tilt to within +/- 0.1° degree, and to determine visual fixation point within +/- 2°, which easily allowed it to fulfill its intended role of determining when the participant was looking at the OTW scene versus when he/she was looking at the instrument panel.

Task Procedures and Dependent Variables

When participants arrived at the lab, they were greeted, escorted to an office, and asked if they had any questions on the informed consent and privacy act statements, which had been e-mailed to them previously. All questions were answered. Participants were reminded that participation was completely voluntary. They were then asked if they were ready to sign the informed consent form. All participants agreed to sign the form and to participate in the study.

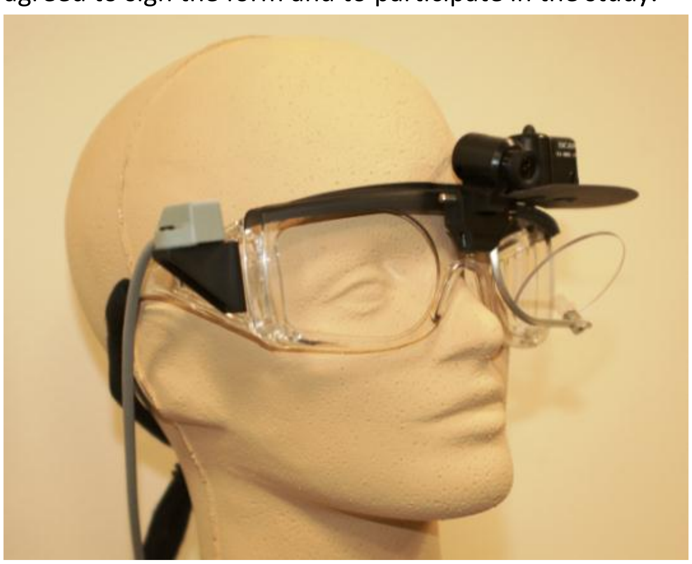

Figure 3. The ISCAN AA-ETL-600 Head and Eye Tracking System™.

Participants were next escorted to the Spatial Disorientation Lab where the experimenter helped them don and adjust the eye-tracking glasses. Participants then sat down in the simulator cockpit and the

eye-tracker was calibrated. The experimenter next gave a short briefing on the cockpit controls and displays, and explained the upcoming flight scenarios.

There were two different flight scenarios used in this study: the Balloon Chase Scenario and the Formation Flight Scenario (see Table 1). Each participant flew each scenario in each of the three FOVs.

Table 1. Fields of View and scenarios experienced by the participants.

	Field of View		
	Small	Medium	Large
Balloon Chase Scenario	• Practice • 2 Flights	• Practice • 2 Flights	• Practice • 2 Flights
Formation Flight Scenario	• Practice • 4 Flights	• Practice • 4 Flights	• Practice • 4 Flights

Balloon Chase Scenario

In the Balloon Chase Scenario, the participant's task was to fly to eleven different large, stationary, spherical balloons spaced 1800 feet apart and offset from each other by 45° (see Figure 4). All balloons were 20 meter in diameter and placed at an altitude of 2500 feet Mean Sea Level (MSL), over flat terrain that had an elevation close to sea level. Skies were clear and visibility was excellent at 25 statute miles. Only two balloons appeared at any given time: the target balloon, which was green, and the balloon beyond, which was red. When the participant's aircraft closed to within 500 feet of the target balloon, that balloon disappeared, the red balloon turned green becoming the new target balloon, and a new red balloon appeared in the distance, again offset 45° to the green target balloon. This sequence repeated until the participant flew to within 500 feet of the last balloon, whereupon that balloon disappeared and the 3.0 minute trial ended.

For each of the three FOVs, participants flew one Balloon Chase practice flight, followed by two Balloon Chase data collection flights. Each flight started with the aircraft headed directly toward the first balloon, so no turn was required until that balloon disappeared. The ten required turns then alternated between left and right. The two Balloon Chase data collection flights were mirror images of each other; that is, in the first flight, the first turn was to the left, whereas in the second flight it was to the right. Participants were instructed to turn "fairly aggressively" in order to quickly line up with the next balloon, but no bank angle was specified. All flights began at 180 knots indicated air speed (KIAS), with the aircraft trimmed for level flight and in the clean configuration.

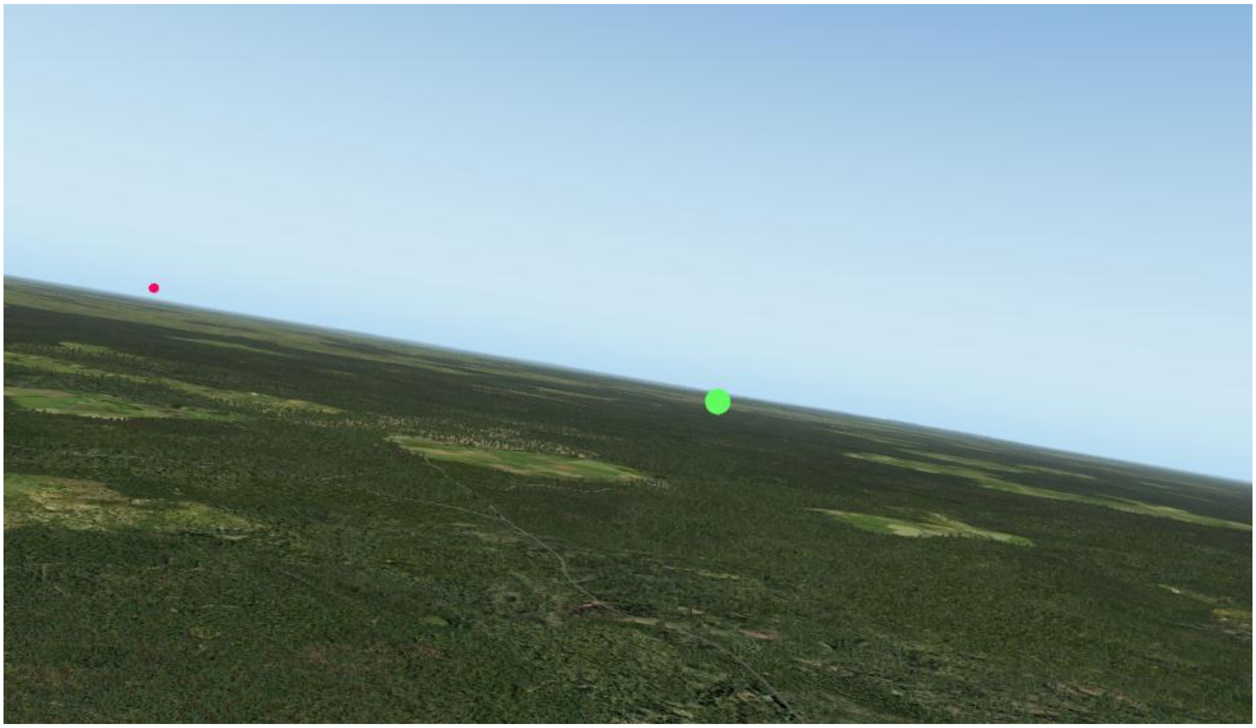

Figure 4. Screen shot from the Balloon Chase Scenario.

Participants were assigned to one of the six possible FOV presentation orders in the following manner. The first presentation order was randomly chosen without replacement; that order turned out to be Large, Small, Medium. The second presentation order was randomly chosen with the constraint that the first FOV was the same as the last FOV from the previous presentation order (in this case, Medium). This procedure minimized the number of times that the cockpit had to be moved between the different FOV screens. Minimization of moves was important because it reduced the wear-and-tear on the cockpit and its electrical connectors. The procedure was repeated until all six possible orders were exhausted. The same sequence of presentation orders was used for the second set of six participants, and Appendix A shows the resulting order for all 12 participants.

For the Balloon Chase flights, the dependent variable of primary interest was Head Tilt Angle as a function of Aircraft Angle of Bank (AOB). These data were sampled and recorded at 10 Hz. After completing the Balloon Chase flights, the simulator transitioned to the next scenario, Formation Flight, using that same FOV.

Formation Flight Scenario

In the Formation Flights, the participant's task was to follow a lead aircraft through a series of turns, climbs, and descents. The flight began at 9500 feet MSL, 500 feet above a level undercast (cloud deck) that completely obscured the ground but still provided a definite, level horizon (see Figure 5). The participant's aircraft was positioned 0.2 nautical miles (370 meters) behind the lead aircraft at a speed of 165 KIAS, matching the lead in speed. Visibility above the clouds was again set to 25 statute miles.

Participants were told to fly in trail formation and that spacing was not critical, but that they should stay close enough to easily see the lead aircraft's attitude.

Figure 5. Screen shot from the Formation Flight Scenario showing a typical view of the lead aircraft while in a right turn.

In the first two Formation Flights, the lead aircraft flew straight and level for 15 seconds, and then entered the first of eight turns, each with a heading change of 90° and a bank angle of approximately 45° (see Appendix B for detailed parameters of the turns). There were four turns to the left and four to the right. One was a climbing turn, and two were descending turns. The sixth turn was descending and it brought the flight into the clouds, but the lead remained visible for two more turns. In the clouds, and ten seconds into the eighth turn, the lead disappeared and the participant's task was to transition to instruments, level the wings, and initiate a shallow climb. These flights lasted approximately 3.4 minutes.

The third and fourth Formation Flights were simply shortened versions of the first two Formation Flights, with the lead aircraft disappearing ten seconds into the descending turn in the clouds (the sixth turn). The early disappearance was included to reduce the predictability of the flights and to possibly introduce an element of surprise. The duration of these flights was approximately 3.1 minutes.

The dependent variable of primary interest for the Formation Flights was the number of CREs. Head Tilt Angle and Aircraft AOB were also recorded.

Simulator Sickness Questionnaire

In order to check for any effect that FOV might have on any incidence of simulator sickness, participants filled out the abbreviated version of the Simulator Sickness Questionnaire (SSQ; 5). The questionnaire (see Appendix C) has 16 items/symptoms which are scored on a 4-point scale (0 = *None*, 1 = *Slight*, 2 =

Moderate, and 3 = *Severe*; see Appendix C). Each symptom on the SSQ belongs to at least one of three subscales: Nausea, Oculomotor, or Disorientation. Each subscale consists of seven symptoms, and some symptoms belong to more than one subscale. The Nausea subscale includes General Discomfort, Salivation Increasing, Sweating, Nausea, Difficulty Concentrating, Stomach Awareness, and Burping. The Oculomotor subscale is comprised of General Discomfort, Fatigue, Headache, Eye Strain, Difficulty Focusing, Difficulty Concentrating, and Blurred Vision. Finally, the disorientation subscale includes Difficulty Focusing, Nausea, Fullness of the Head, Blurred Vision, Dizziness with Eyes Open, Dizziness with Eyes Closed, and Vertigo. Details on how the subscales are differentially weighted can be found in Kennedy (6).

The SSQ was administered for a baseline measurement before participants flew their first FOV and again after each FOV (session) was completed. After filling out the questionnaire, participants were given a five-minute break as the cockpit was moved to the next FOV.

RESULTS

Opto Kinetic Cervical Reflex

To determine if participants were exhibiting typical head tilt behavior while flying this simulator, average head tilt across all participants was plotted as a function of aircraft AOB, in 5° aircraft bank angle increments. The plots were limited to +/- 60° AOB because there were relatively few data points for aircraft bank angles beyond those values. These head tilt functions were plotted for the Balloon Chase flight (which always had a visible horizon), Formation Flight outside of clouds (visible horizon), and Formation Flight within the clouds (no horizon). The plotted points in Figure 6 represent the head tilt average for the two Balloon Chase flights, whereas Figure 7 presents those points for the four Formation Flights while outside of clouds, all averaged across FOV. These plots clearly show that with a visible horizon, as participants banked the aircraft in one direction they tilted their heads in the opposite direction (back toward the horizon), and that head tilt increased with aircraft AOB, confirming the typical OKCR results found in previous studies.

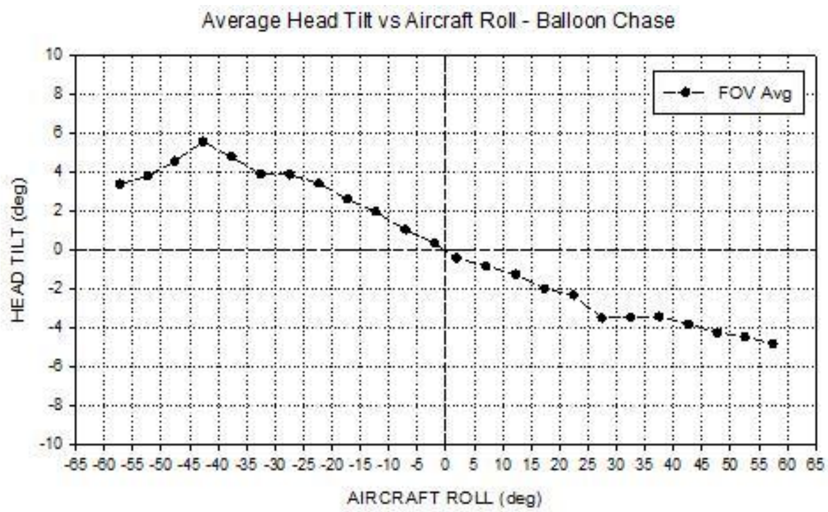

Figure 6. Average head tilt vs. aircraft roll across all FOVs in the Balloon Chase Scenario.

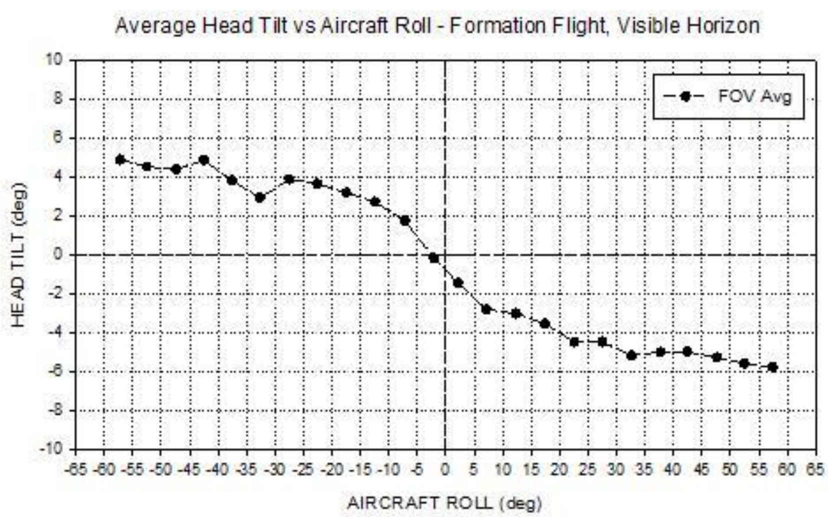

Figure 7. Average head tilt vs. aircraft roll across all FOVs in the Formation Flight Scenario with a visible horizon.

The same plot was generated for Formation Flights in the clouds where there was no visible horizon; these results are shown in Figure 8. The shallower slope of the line indicates that participants exhibited less head tilt behavior when only the lead aircraft, and not the horizon, was visible.

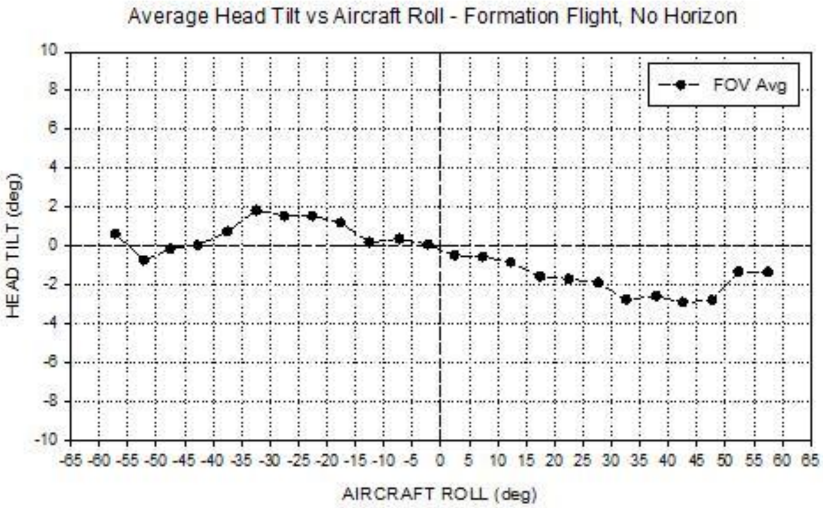

Figure 8. Average head tilt vs. aircraft roll across all FOVs in the Formation Flight Scenario, no visible horizon.

Figures 9 – 11 present the same data as Figures 6 – 8, but in more detail because they break out the different FOVs. Although "noisier," these plots again indicate that when the horizon is visible, pilots increase head tilt with increasing aircraft AOB and that the response is attenuated in the clouds.

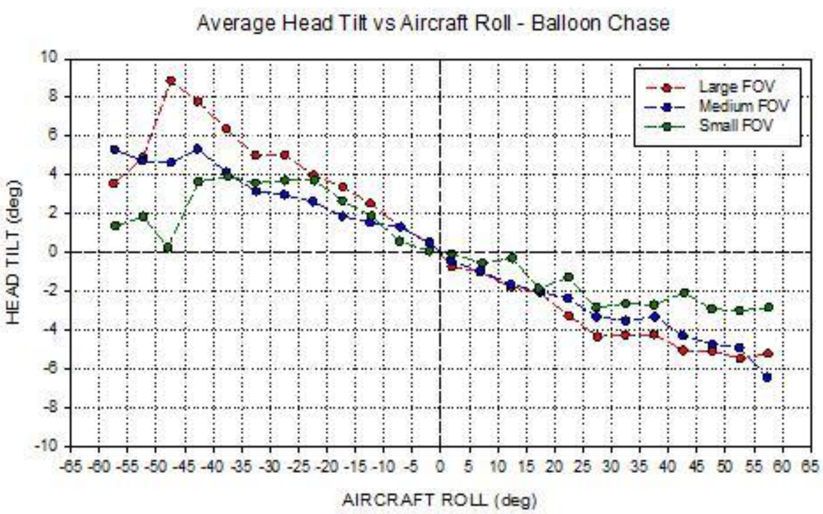

Figure 9. Average head tilt vs. aircraft roll for each FOV in the Balloon Chase Scenario.

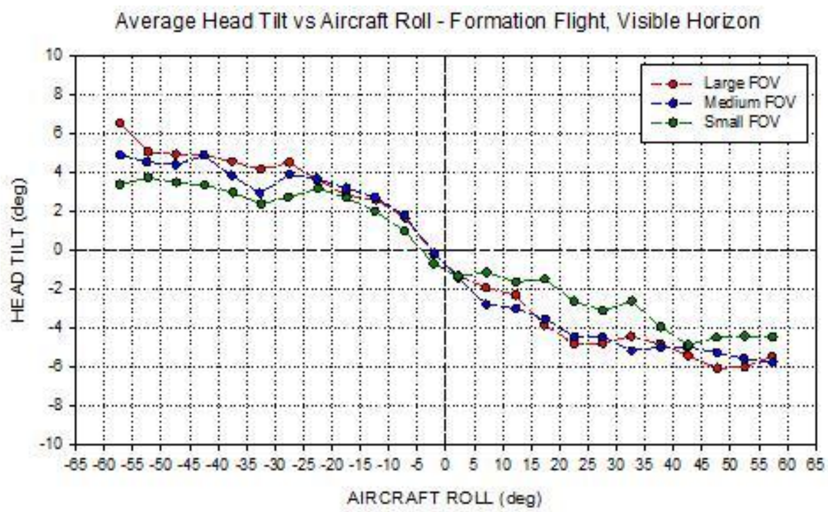

Figure 10. Average head tilt vs. aircraft roll for each FOV in the Formation Flight Scenario with a visible horizon.

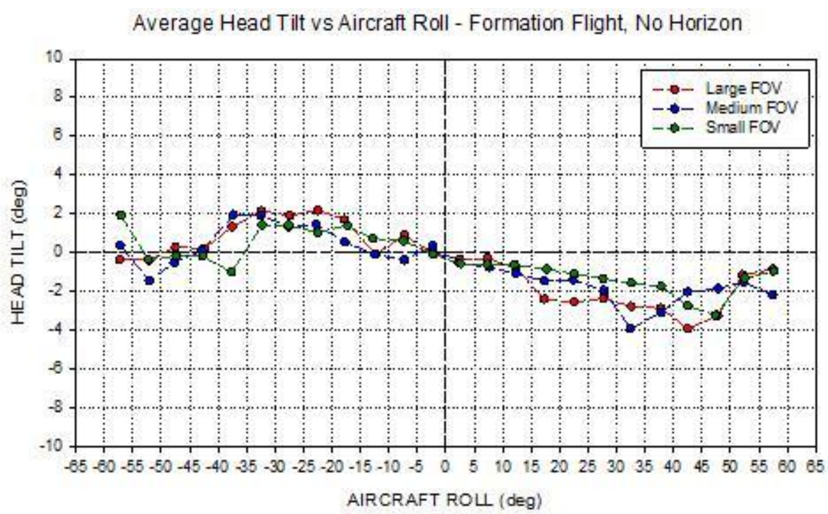

Figure 11. Average head tilt vs. aircraft roll for each FOV in the Formation Flight Scenario, no visible horizon.

To determine if AOB and FOV had statistically significant effects on head tilt, the data represented in Figures 9, 10, and 11 were entered into three separate within-subjects ANOVAs. For each ANOVA there were 24 levels of AOB (comparable to analyses from previous head tilt studies) and three levels of FOV. The 3 x 24 ANOVA for the Balloon Chase data (Figure 9) confirmed a significant effect for AOB ($F_{(23, 253)}$ = 11.58, p < .001), with increasing AOB inducing increased head tilt back toward the horizon. There was no significant effect for FOV ($F_{(2, 22)}$ = 0.16, p >.05), but the interaction was significant ($F_{(46, 506)}$ = 4.10, p < .001).

When the corresponding ANOVA was performed on the Formation Flight – Visible Horizon data (Figure 10), the pattern of results was identical. The effect of AOB on head tilt was significant ($F_{(23, 253)}$ = 47.5, p < .001), and there was no significant effect for FOV ($F_{(2, 22)}$ = .19, p >.05). The interaction was again significant ($F_{(46, 506)}$ = 3.27, p < .001).

A similar ANOVA was performed on the Formation Flight – No Horizon data (Figure 11), and the AOB effect was still significant with no visible horizon ($F_{(23, 253)} = 10.62$, $p < .001$). Neither the FOV effect ($F_{(2, 22)} = 0.41$, $p > .05$) nor the interaction ($F_{(46, 506)} = 1.05$, $p > .05$) were significant.

As a second way to analyze the relationship between aircraft AOB and head tilt, Pearson product moment correlation (*r*) values were calculated between these two variables. This was done for each pair of AOB and head tilt data points, which were sampled at 10 Hz, yielding high resolution and a very large number of observations. For example, each 3.0 min Balloon Chase flight produced 1800 data pairs. The mean values for *r* are listed in Table 2 for the different FOVs and for each scenario/flight condition. The negative *r* values confirm that the head tilt occurred in the direction opposite of aircraft bank; that is, participants were tilting their heads back toward the horizon. Even though the *r* values for flight with no horizon (Formation in the clouds) were markedly lower than those for flight with a visible horizon (Balloon Chase and Formation above the clouds), all *r* values were significant ($p < .05$).

<u>Table 2.</u> Mean *r* values between aircraft AOB and head tilt for each FOV and scenario/flight condition. The mean in each cell is across all 12 participants, and across the two Balloon Chase Flights or the four Formation Flights.

	Small	Medium	Large
Balloon Chase	-0.25	-0.49	-0.48
Formation Flight: Visible Horizon	-0.56	-0.65	-0.71
Formation Flight: No Horizon	-0.09	-0.09	-0.11

*All *r* values were significant at the $p < .05$ level.

Figure 12 illustrates the data from Table 2 for the Balloon Chase flights. In order to determine if the strength of association between AOB and head tilt varied significantly as a function of FOV, *r* values were first converted to *Z*-scores for normalization purposes, and then entered into a 1 x 3 within-subjects ANOVA. There was a significant effect for FOV, $F_{(2,22)} = 8.81$, $p < .01$. Planned pairwise comparisons revealed that the association between head tilt and aircraft AOB was significantly stronger for the Large FOV as compared to the Small FOV ($p < .05$) and again for the Medium FOV compared to the Small FOV ($p < .01$). The Large and Medium FOVs were not significantly different from each other.

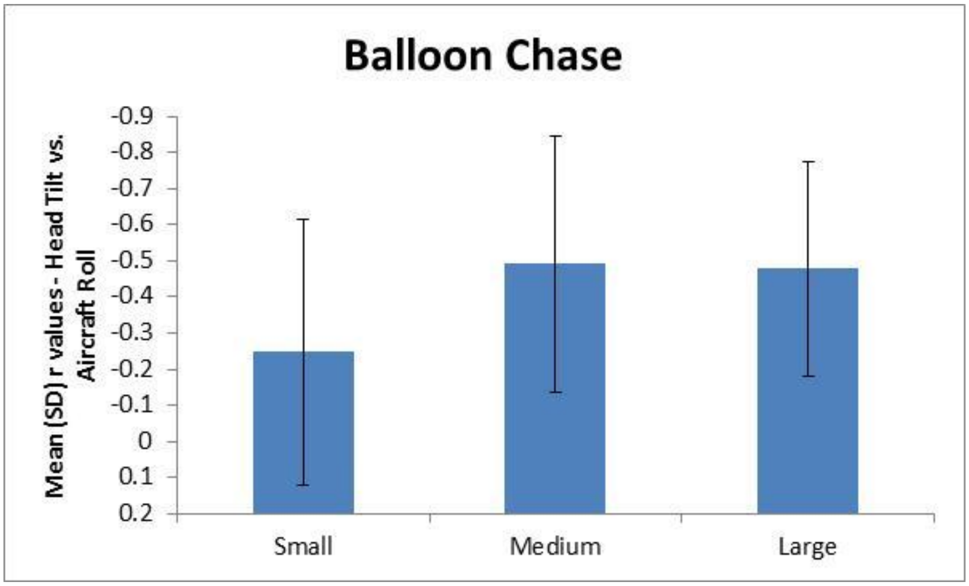

Figure 12. Mean *r* values between head tilt vs. aircraft AOB in the Balloon Chase Scenario. Plotted values span the abscissa to accommodate error bars, which encompass ± 1 Std dev.

Figure 13 shows the data from Table 2 for the Formation Flights when the horizon was visible. A 1 x 3 within-subjects ANOVA on the *Z*-transformed correlations yielded the same pattern of results as that for the Balloon Chase flights. There was a significant effect for FOV $F_{(2,22)} = 6.67$, $p < .01$, with planned comparisons showing that the Large and Medium FOVs each had a significantly larger effect than did the Small FOV ($p < .05$), but the former two did not differ from each other.

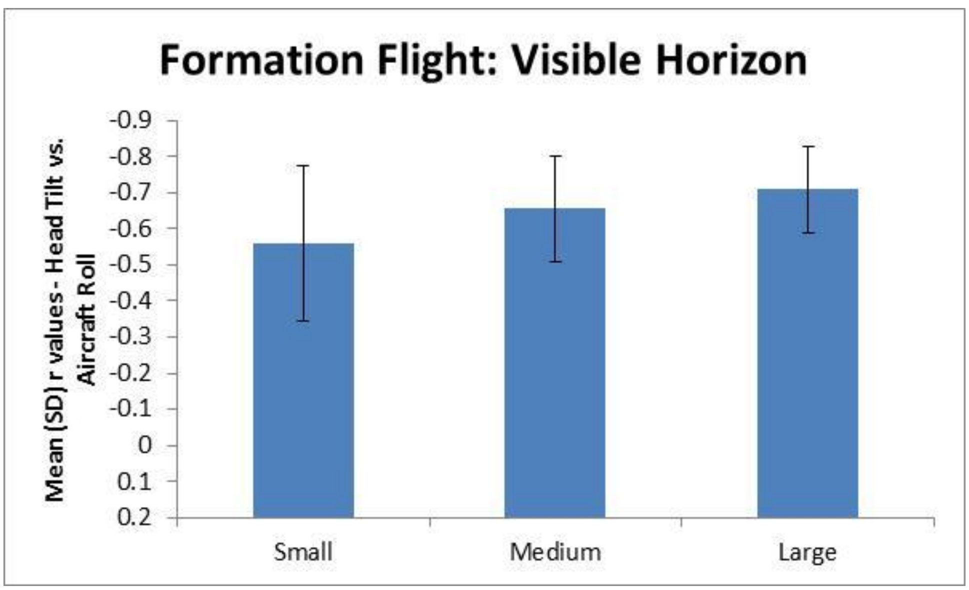

Figure 13. Mean *r* values between head tilt vs. aircraft AOB in the Formation Flight Scenario with a visible horizon. Error bars encompass ± 1 Std dev.

Figure 14 portrays the relationship between head tilt and aircraft AOB for each of the three FOVs when the horizon was not visible. A 1 x 3 within-subjects ANOVA on these normalized data revealed no

significant effect of FOV, $F_{(2,22)} = 2.10$, $p > .05$. That is, with no visible horizon, the strength of association between head tilt and aircraft AOB did not change significantly across the different FOVs.

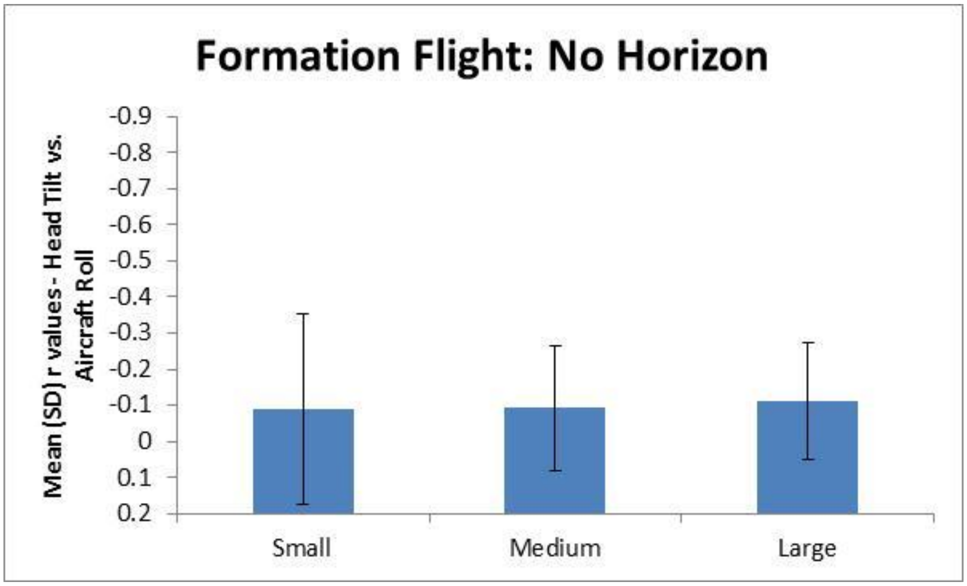

Figure 14. Mean *r* values between head tilt vs. aircraft AOB in the Formation Flight Scenario, no visible horizon. Plotted values span the abscissa to accommodate error bars, which encompass ± 1 Std dev.

Control Reversal Errors

Each of the 12 participants flew 12 Formation Flights, so there was a total of 144 flights on which a CRE could have been committed. On four of these flights, pilots prematurely lost sight of the lead in the clouds and could not re-establish visual contact, so those four flights were not included in the CRE analysis.

For the purposes of this study, a CRE was defined as joystick roll input in the direction opposite to that required for a wings-level recovery. A threshold for the magnitude of stick movement was defined as at least 15% of the movement possible in either direction, which translates into an errant stick movement of 1.7 cm to the left or right. Analysis of the stick movement data revealed a total of 17 CREs in 140 flights, for a CRE rate of 12.1%. Four of the twelve participants (33.3%) committed at least one CRE. Table 3 shows the number of CREs and flight hours for each of these four participants, as well as whether or not they had an instrument rating. The number of CREs for each FOV is plotted in Figure 15.

Table 3. Number of CREs, flight hours, and instrument rating status for the four participants who committed CREs. Data are sorted by number of CREs.

Participant	Number of CREs	Flight Hours	Instrument Rated?
CRE 1a	1	105	N
CRE 1b	1	150	Y
CRE 7	7	1500	Y
CRE 8	8	100	N

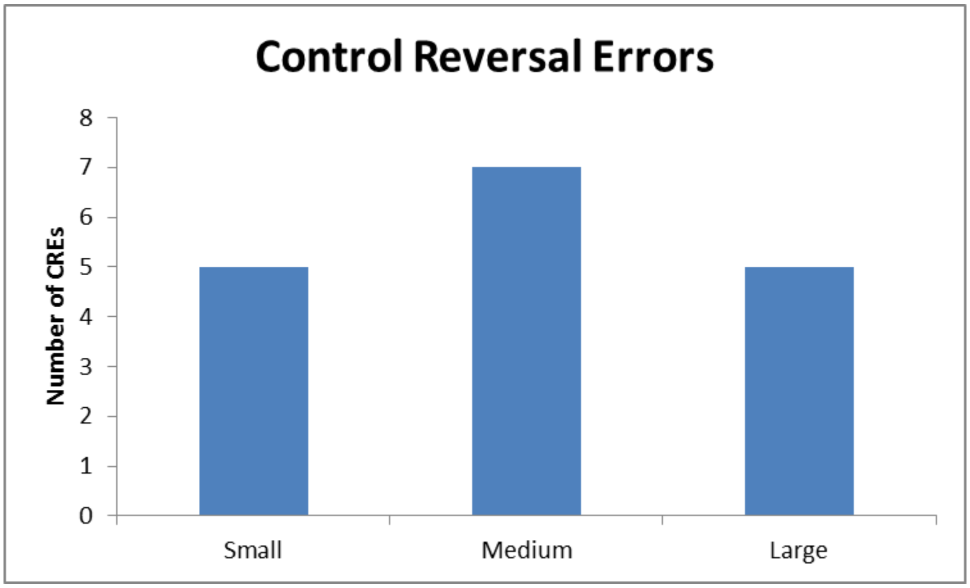

Figure 15. Number of CREs committed on each FOV.

A logistic regression was run on the CRE data with FOV, instrument rating, and flight hours as factors, and number of CREs as the outcome variable. The results revealed that FOV was not a significant predictor of committing CREs (Wald $X^2_{(1, N = 144)} = .53$, $p > .05$). The results did, however, reveal that instrument rating (Wald $X^2_{(1, N = 144)} = 4.65$, $p < .05$), and flight hours, (Wald $X^2_{(1, N = 144)} = 9.79$, $p < .01$), were significant predictors of CREs. Having an instrument rating and having more flight hours resulted in a *decreased* likelihood of committing CREs. It should be noted that an instrument rating requires additional flight training, so pilots with that rating also tend to have more flight hours.
In examining the model for goodness of fit, a backwards stepwise analysis revealed that flight hours, accounting for 21% (Nagelkerke $R^2 = .21$) of the total CRE variance, was the best predictor of CREs. Instrument rating and FOV only accounted for an additional 1% of the total variance and removing them from the model did not result in a significant change ($p > .05$).

Simulator Sickness Questionnaire (SSQ)

The 16 items on the SSQ were rated on a 4-point scale (0 = *None*, 1 = *Slight*, 2 = *Moderate*, and 3 = *Severe*; see Appendix C). Participants completed the SSQ four times (baseline and after each FOV) during the experiment. Figure 16 shows the average response by FOV, whereas Figure 17 shows the same data across sessions (i.e., Baseline, 1st, 2nd, and 3rd FOV session).

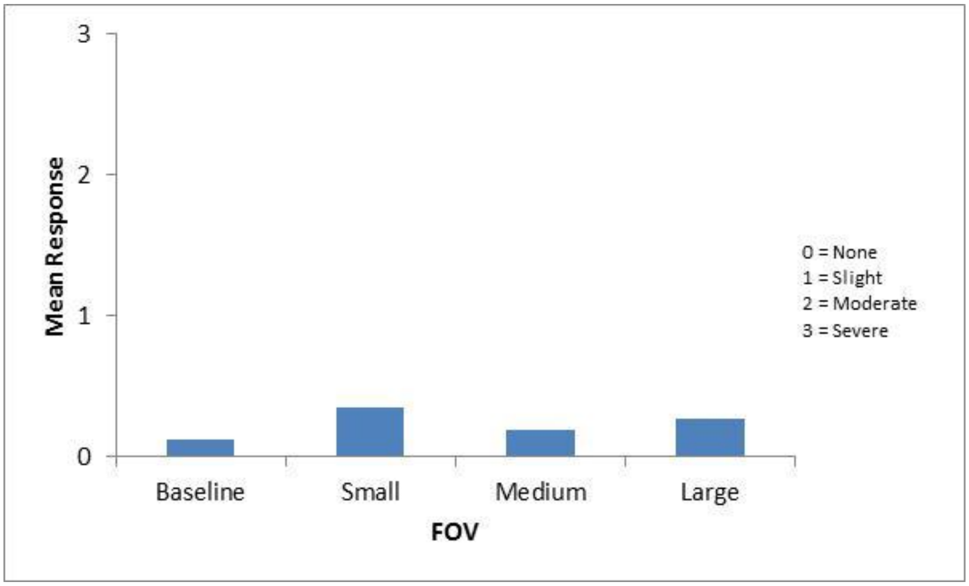

Figure 16. Mean SSQ responses for Baseline and the three FOVs.

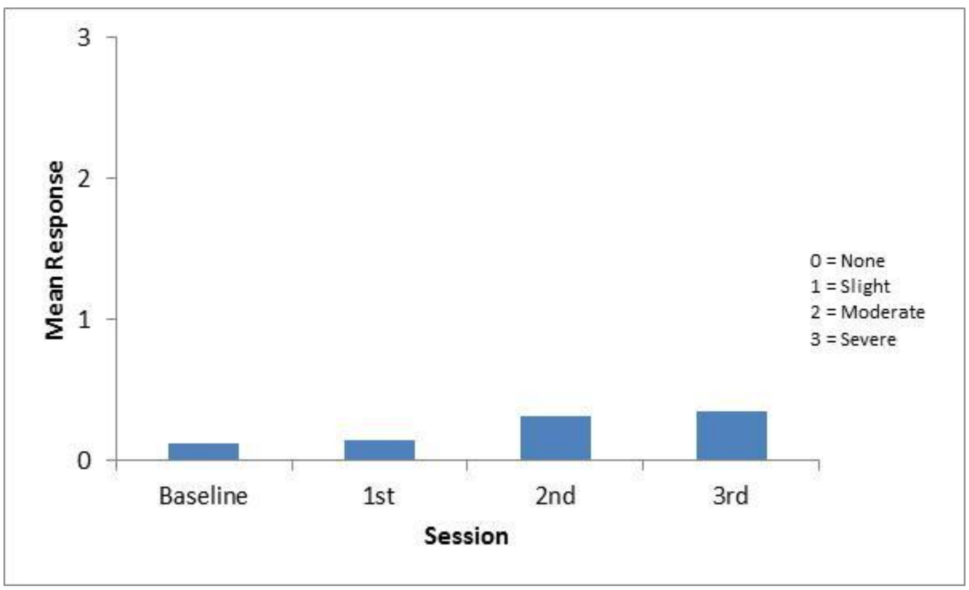

Figure 17. Mean SSQ responses for sessions.

By far the most common response on the questionnaire was *None* with 723 of the total 768 (96%) responses falling into that category. Half of the subjects (6 of 12) reported *None* for every item throughout the entire experiment. For eight of the symptoms, every participant responded *None* in every instance, for baseline and for every FOV. These symptoms, which are generally associated with motion sickness and disorientation, were: Nausea, Sweating, Increased salivation, Dizziness eyes open, Dizziness eyes closed, Vertigo, Stomach awareness, and Burping. The remaining eight symptoms did receive some ratings of *Slight* which was used 45 times (6%) and was the highest rating given to any of the symptoms (see Figure 18). The eight symptoms which received a *Slight* rating on occasion were: General discomfort, Fatigue, Headache, Eye strain, Difficulty focusing, Difficulty concentrating, Fullness

of head, and Blurred vision. Figure 18 shows the total number of times each symptom was reported as *Slight* by any of the 12 participants, and it shows the responses across simulator session (time). The most commonly reported symptom was eyestrain, and at its peak 5 of the 12 participants gave it a rating of *Slight* after their final simulator flight. Note that 1 of these 5 participants reported slight eyestrain as a baseline rating, before starting the eye tracker calibration process and before sitting down in the simulator for the first time.

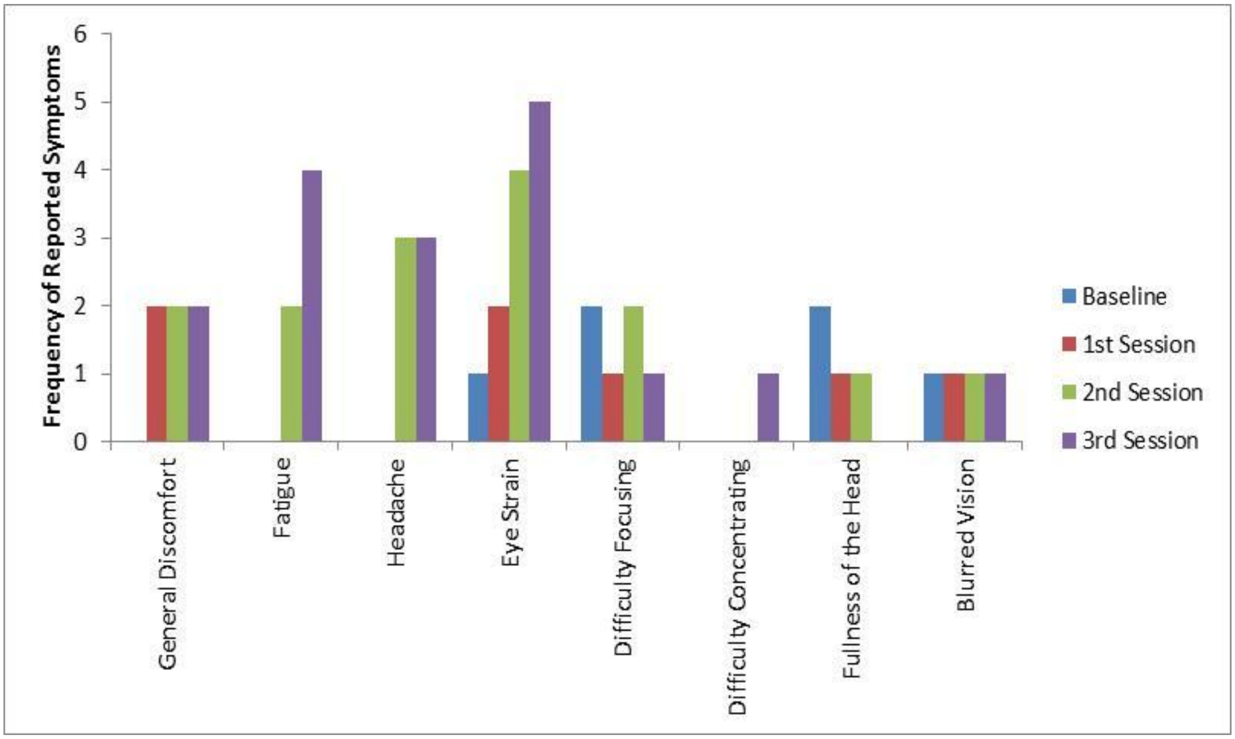

Figure 18. Frequency of symptoms reported as *Slight* broken down by time. No ratings greater than *Slight* (i.e., *Moderate* or *Severe*) were reported by any of the participants for any of the symptoms.

After sorting and tabulation, the SSQ data were weighted and processed according to procedures outlined in Kennedy (6) to calculate sub-scale scores. These scores are presented in Table 4 as a function of FOV, and as a function of simulator session (i.e., across time). For each subscale, Friedman Tests were conducted to see if there was any FOV effect. The analyses revealed no significant differences between FOVs for any of the subscales nor for total SSQ score ($p > .05$). However, the same type of analyses across time revealed that within the Oculomotor subscale, ratings increased significantly across time ($X^2_{(3)} = 11.85$, $p < .01$), and the same pattern was reflected in the total SSQ score ($X^2_{(3)} = 10.37$, $p < .05$). Focusing in on the Oculomotor ratings, Wilcoxon Tests were used to compare Baseline ratings with the 1st, 2nd, and 3rd simulator session ratings. These analyses revealed no significant difference between the Baseline and 1st session ($Z = 1.00$, $p > .05$); however, the Oculomotor ratings increases were significant between Baseline and 2nd ($Z = 1.98$, $p < .05$) and Baseline and 3rd sessions ($Z = 2.14$, $p < .05$).

Table 4. *Mean (SE) SSQ scores as a function of FOV and session*.

		Nausea	Oculomotor	Disorientation	Total
FOV	Baseline	0.00 (0.00)	2.53 (1.94)	5.80 (3.62)	2.81 (1.91)
	Large	2.39 (1.25)	8.21 (3.16)	2.32 (2.32)	5.61 (2.13)
	Medium	0.80 (0.80)	5.05 (2.15)	4.64 (2.62)	4.05 (1.75)
	Small	2.39 (1.25)	10.11 (3.88)	3.48 (2.50)	6.86 (2.68)
Time	Baseline	0.00 (0.00)	2.53 (1.94)	5.80 (3.62)	2.81 (1.91)
	1st Session	1.59 (1.07)	3.79 (1.98)	3.48 (2.50)	3.43 (1.69)
	2nd Session	1.59 (1.07)	8.84 (3.21)	4.64 (2.62)	6.23 (2.32)
	3rd Session	2.39 (1.25)	10.74 (3.79)	2.32 (2.32)	6.86 (2.51)

DISCUSSION

The major goal of this project was to determine if three different non-motion simulator FOVs, each practical for most military aviation training environments, varied in their ability to elicit OKCR Head Tilt and/or CREs. Since OKCR and CRE may contribute to, and result from SD, it is important to be able to produce these responses for SD training. From cost and space standpoints, smaller FOVs are generally preferred for SD training, provided that the ability to produce the desired sensory spatial responses is not compromised. Ultimately this work was aimed at helping to find the right balance between FOV size and training effectiveness, and to apply this information to the SD simulator acquisition process currently being planned by NAVAIR.

ANOVAs on the raw OKCR head tilt data and on the *r* values confirmed that when the horizon was visible, head tilt increased significantly with AOB (Figures 9 & 10). This main effect is straightforward and consistent with previous research (1, 4, 9, 11, 13). When the 3 x 24 ANOVAs were run on Head Tilt as a function of FOV, no significant FOV main effects were observed. However, the interaction between FOV and AOB was significant and close examination of Figures 9 and 10 show this interaction in the form of non-parallel lines. More specifically, the lines for the Large and Medium FOVs tend to cross the line for the Small FOV, and the former two generally show slightly more head tilt at greater AOBs. In support of this observation, when *r* values were analyzed it was found that the strength of association between AOB and Head Tilt was stronger for the Medium and Large FOVs as compared to the Small FOV. Thus the ANOVAs on the *r* values were able to detect an FOV effect, with the Medium and Large FOVs producing a stronger association than the Small FOV, and this pattern of results was observed for the two different types of flight tasks: conducting turns between static waypoints in the Balloon Chase, as well as following a dynamically maneuvering lead aircraft in the Formation Flights.

It is worthwhile to note here that the 3 x 24 ANOVAs differed from the *r* value ANOVAs in the sense that the former were not looking at strength of association per se, but rather at the magnitude of the head tilt itself as a function of FOV. Visual inspection of Figures 9 and 10 suggests that head tilt magnitude did increase some with increasing FOV size, but the 3 x 24 ANOVAs were not able to confirm any such increase as a significant main effect. With the addition of the ANOVAs on *r* values, it can be said that

head tilt behavior tracks more consistently with changing aircraft AOB as FOV increases (see Figures 12 and 13), even if the magnitude of the head tilt does not increase significantly. The results also showed that the Medium FOV system, which costs approximately 30% less and occupies 70% less volume than the Large, produced a consistency better than the Small but statistically (and practically) indistinguishable from the Large FOV. These are important findings since they enable a practical and empirically based recommendation: the Medium FOV, with its lower price point and smaller form factor, is a cost effective and efficient visual system solution for SD training scenarios where it is important to consistently induce the OKCR head tilt reflex.

Compared to flight with a visible horizon as discussed above, when participants were following the lead aircraft through turns in the clouds the OKCR was greatly reduced, but still present. Similar results have been reported by other researchers as well (1). The smaller OKCR in the current study can be seen in Figures 8 and 11, and in the small but statistically significant correlations presented in the last row of Table 2. This subtle head tilt response raises a question as to why any head tilt occurred at all with no visible natural horizon. A first thought might be to assume that in the clouds, the lead aircraft becomes a primary spatial cue, and its wings now become a "mini-horizon". As the lead aircraft begins a turn its changing roll attitude could trigger a small OKCR, but if that were the case we would expect the shape of the curve in Figures 8 and 11 to be reversed. If the lead rolled to the left, the participant would be expected to roll his/her head also to the left in an attempt to maintain some horizontal head alignment with the bank angle of the lead's wings. But instead, participants exhibited a small but classic OKCR by counter-tilting against the turn.

A better explanation as to why the small OKCR still occurred without a visible horizon is simple force of habit. Pilots may become conditioned to counter-tilt their head as they roll into a turn, but with no visible horizon, a full OKCR is never activated. A second and probably more remote possibility is that the artificial horizon (attitude indicator) on the instrument panel triggers an attenuated OKCR. Although pilots should have been focusing on the lead aircraft, the artificial horizon would still be visible in the periphery. An interesting follow-on experiment would be to run the scenarios with and without an artificial horizon to see if the OKCR is completely extinguished in the absence of that instrument.

Another question prompted by the OKCR results from this study and previous work has to do with the ratio between head tilt and aircraft AOB. For a relatively small AOB such as 15°, it would be entirely possible and comfortable for a pilot to match AOB with head counter-tilt on a 1:1 basis. However, if we examine Figure 7, we see that for a 15° aircraft bank angle, participants only tilted their heads approximately 3° on average. Similar patterns of results can be seen in the data reported by others (1, 4, 9, 11, 13). A question then arises as to why pilots undercompensate with head tilt. As a partial answer, there is another mechanism by which the visual system can help keep the transverse axis of the eye aligned with the horizon, and that is eye torsion. The eye can actually roll in its socket, basically on the same axis as the line of sight, up to about 7°. One flight simulator study using 45° AOB turns found that participants' eyes torqued an average of 2.0°, with an additional 3.6° of head tilt, for a total compensation of 5.6°. Thus while eye torsion helps compensate in combination with head tilt, pilots still do not seem to keep the retinal image of the horizon aligned with the transverse axis of the eye when it would be easy to do so, especially at smaller bank angles. Eye torsion was not measured in the current

study, but doing so in future work, along with scenarios specifically designed to examine this issue, may help answer the question of why pilots undercompensate to the degree that they do.

As a final observation on the OKCR results, visually comparing the *r* values in Table 2 for the Balloon Chase, Formation Flight - Visible Horizon, and Formation Flight - No Horizon shows that the latter condition clearly produced the smallest correlation between aircraft AOB and Head Tilt. This result makes sense because there was no visible horizon with which participants would try to align their heads. The Balloon Chase flights produced stronger correlations, and Formation Flight – Visible Horizon correlations were stronger still. Other studies (5, 11) have found stronger OKCRs for low-level versus cruise-altitude flight. Due to low level flight's close proximity to the ground, there is a greater sensation of speed and a smaller margin for error, so the horizon likely becomes even more important for pilots as a cue to maintaining proper aircraft attitude. In the current study, although Formation – Visible Horizon flights were conducted at 9500 feet MSL, the aircraft was only 500 feet above the textured cloud deck, and this was very comparable to a low level flight over flat terrain. The Balloon Chase flights were conducted approximately 2500 feet above ground level, and from the pilot's perspective, these flights were arguably more representative of a cruise environment, versus a low level environment. It is likely that the Formation Flight's similarity to low level flight strengthened the OKCR, as compared to the Balloon Chase flight, explaining the overall pattern of results in Table 2.

CRE

CREs are an important topic in SD research because they can both result from, and contribute to, SD. For example, consider a disoriented pilot who is in a turn and wants to return to level flight. Because of SD, the pilot is confused about the aircraft's true attitude, and is more likely to misinterpret the roll information from the attitude indicator. Due to this misinterpretation, the pilot moves the stick in the wrong direction, committing a CRE. The attitude indicator responds by moving in the unexpected direction, which can worsen the SD. If the pilot does not recover quickly, the flight may end in a serious mishap.

For training purposes, it would be very useful to be able to safely expose pilots to such a situation so that the first time they have to solve this problem is <u>not</u> during an actual, operational, solo flight. Because it can be difficult to recreate this scenario in the air during a training flight, and because airborne training hours are expensive, simulation is an attractive option. Thus the ability to induce CREs in safe and relatively inexpensive flight simulation has great value for SD training.

In this experiment we were able to induce CREs in one-third of the pilots and on 12.1% of the trials, and these results are comparable to other studies where the recovery task was fairly simple (i.e., low workload, moderate bank and pitch angles (7)). Flight experience, expressed in flight hours, was the single best predictor of CREs, with more experienced pilots being less likely to commit CREs. Whether or not a pilot had an instrument rating was also a significant predictor; pilots with that rating were less likely to commit a CREs, but information on that status did not significantly increase the variance accounted for if the number of flight hours was available.

It is important to note that this experiment's success in inducing CREs was accomplished under low workload conditions with no distractions, the bank angles were moderate, and pilots had at least some expectation that they would need to transition to instruments and initiate the recovery. By increasing workload, distraction, and event uncertainty, it is likely that this training scenario can be improved to increase the probability of safely exposing pilots to CRE situations. A worthwhile future research effort would be to systematically manipulate these variables to better understand and optimize CRE probability.

A very important practical finding from the current research was that CRE probability was not dependent upon FOV. The Medium FOV, which fared well in terms of inducing OKCR, also did very well in inducing CREs. It produced seven CREs whereas the Small and Medium FOVs each produced five. This increase in CREs was not statistically significant, but overall the results further strengthen the Medium FOV as a sound choice for SD training, avoiding the additional cost and space requirements associated with a Larger FOV system.

SSQ

Overall the SSQ ratings were very low. The most frequent rating given for all of the symptoms was *None,* accounting for an overwhelming majority of 94% of all responses. Half of the participants chose this response for every SSQ item throughout the experiment. Eight symptoms which are commonly associated with simulator sickness (Nausea, Sweating, Increased salivation, Dizziness eyes open, Dizziness eyes closed, Vertigo, Stomach awareness, and Burping) received ratings of *None* from every participant in every instance. These results indicate that there were no simulator sickness problems with any of the FOVs.

For the remaining eight SSQ symptoms, participants gave an occasional rating of *Slight,* and these ratings rounded out the remaining 6% of all responses. These eight symptoms and their response patterns are depicted in Figure 18. It is important to reiterate that there were two other response choices, *Moderate* and *Severe* that were never invoked. These results reinforce the conclusion that at least for the symptoms addressed by the SSQ, none of the FOVs used in this study created any concerning issues.

Participants did introduce some response variability by answering *Slight* in some instances, and the data were analyzed using non-parametric statistics. When the weighted SSQ sub-scale responses were examined with FOV as a factor, FOV had no significant effect on any of the sub-scale scores, or on the Total SSQ score. When the same data were analyzed with Time (simulator session) as a factor, Oculomotor symptom ratings were found to increase significantly as time in the simulator increased. The Oculomotor scale is comprised of General Discomfort, Fatigue, Headache, Eye Strain, Difficulty Focusing, Difficulty Concentrating, and Blurred Vision, and examination of Figure 18 shows that ratings for most of these symptoms increased as the simulator session wore on. Eye strain was the most common symptom, with 5 of the 12 participants reporting slight eyestrain in the final simulator session. This effect of time spent in the simulator is logical, and is likely a result of participants having to wear the eye tracker device and engage in a visually intensive, sustained attention task for approximately 2.5

hours. It is not surprising that these symptoms would increase over time given the circumstances and nature of the task.

Conclusions & Recommendations

This project set out to determine the appropriate size FOV for procuring or upgrading certain DoD flight simulators that are used for SD training. The following conclusions and recommendations are provided:

- In terms of eliciting the OKCR, the Medium FOV (130° x 60°) was just as effective as the Large FOV, and both the Medium and Large were better than the Small. The Medium FOV induced slightly more CREs than the other two, but the difference was not significant. Aside from some reports of slight oculomotor symptoms (principally eyestrain late into the study), none of the FOVs showed any tendency to induce any simulator sickness. Given the Medium FOV's effectiveness and cost and space savings, this size FOV is recommended for similar SD training purposes.
- The scenarios used in this study required only moderate bank angles and none of the tasks required aggressive maneuvers or unusual attitudes. One-third of the pilots committed CREs and that proportion is typical for flight profiles similar to those used here. To increase the effectiveness of SD training time in the simulator, future research should systematically vary flight profile difficulty and introduce realistic distractions and secondary tasks to manipulate pilot workload levels. Doing so would allow researchers to optimize and fine tune training scenarios. These refinements would likely produce more realistic training, more CREs, and more learning opportunities for pilots to experience and recover from SD.

The recommended simulator specifications and results of this project will be directly shared and discussed with personnel at NAVAIR and at NSTI who actually provide SD training to Navy, USMC, and USCG aircrew. SD simulator acquisition plans are currently in motion at NAVAIR, so these empirically-based recommendations are timely. Since SD affects all aviators, this report and its results should be useful across the DoD, commercial, and general aviation worlds as well.

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Appendix A

	FOV Presentation Order		
Subject	1st	2nd	3rd
1	L	S	M
2	M	L	S
3	S	M	L
4	L	M	S
5	S	L	M
6	M	S	L
7	L	S	M
8	M	L	S
9	S	M	L
10	L	M	S
11	S	L	M
12	M	S	L

Appendix B

Formation Flight 1

	Heading	Duration	Altitude
START	315˚	15 s	9500 MSL
RIGHT	045˚	5 s	9500 MSL
RIGHT	135˚	5 s	9500 MSL
CLIMB LEFT	045˚	10 s	9700 MSL
LEFT	315˚	10 s	9700 MSL
DESCEND RIGHT	045˚	5 s	9500 MSL
DESCEND LEFT	315˚	10 s	9000 MSL
RIGHT	045˚	10 s	9000 MSL
LEFT	315˚	LEAD DISAPPEARS 10 SEC INTO TURN	9000 MSL

Formation Flight 2

	Heading	Duration	Altitude
START	315˚	15 s	9500 MSL
LEFT	225˚	5 s	9500 MSL
LEFT	135˚	5 s	9500 MSL
CLIMB RIGHT	225˚	10 s	9700 MSL
RIGHT	315˚	10 s	9700 MSL
DESCEND LEFT	225˚	5 s	9500 MSL
DESCEND RIGHT	315˚	10 s	9000 MSL
LEFT	225˚	10 s	9000 MSL
RIGHT	315˚	LEAD DISAPPEARS 10 SEC INTO TURN	9000 MSL

Formation Flight 3

	Heading	Duration	Altitude
START	315˚	15 s	9500 MSL
RIGHT	045˚	5 s	9500 MSL
RIGHT	135˚	5 s	9500 MSL
CLIMB LEFT	045˚	10 s	9700 MSL
LEFT	315˚	10 s	9700 MSL
DESCEND RIGHT	045˚	5 s	9500 MSL
DESCEND LEFT	315˚	LEAD DISAPPEARS 10 SEC INTO TURN	9000 MSL

Formation Flight 4

	Heading	Duration	Altitude
START	315˚	15 s	9500 MSL
LEFT	225˚	5 s	9500 MSL
LEFT	135˚	5 s	9500 MSL
CLIMB RIGHT	225˚	10 s	9700 MSL
RIGHT	315˚	10 s	9700 MSL
DESCEND LEFT	225˚	5 s	9500 MSL
RIGHT	315˚	LEAD DISAPPEARS 10 SEC INTO TURN	9000 MSL

Appendix C

Simulator Sickness Questionnaire

Subject Number______________ Date____________________

SIMULATOR SICKNESS QUESTIONNAIRE

Instructions: Circle how much each symptom below is affecting you right now. You will be asked to complete the questionnaire again after flying each of the three simulators.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. Fullness of the Head	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. Vertigo *	None	Slight	Moderate	Severe
15. Stomach awareness **	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.